

QCD at Photon Colliders ^{*}

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Abstract

The novel possibilities of probing the photon structure and high energy limit of QCD at photon colliders are summarised. We discuss the photon structure function $F_2^\gamma(x, Q^2)$, the gluon distribution in the photon and the spin dependent structure function $g_1^\gamma(x, Q^2)$ of the photon and emphasise advantages of the photon colliders for measuring these quantities. The possibility of probing the QCD pomeron and odderon in $\gamma\gamma$ and $e\gamma$ collisions is also described.

1 Introduction

The photon colliders offer unique possibility to probe QCD in a new and hitherto unexplored regime. Very high luminosity and relatively sharp spectrum of the backscattered laser photons are the enormous advantages of the photon colliders making it possible to measure very precisely various quantities as well as to have an access to rare QCD processes. The aim of this introductory talk is to elaborate the following two broad subjects for which the possible measurements at photon colliders may be particularly relevant:

1. The photon structure.
2. High energy QCD.

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The content of our talk is as follows: in the next section we discuss the deep inelastic $e\gamma$ scattering as the tool for probing the quark content of the photon while in Section 3 we consider the measurements which may probe the gluon distributions in the photon. In Section 4 we very briefly summarise the theoretical expectations concerning the high energy behaviour of QCD (i.e. the QCD pomeron and odderon) and discuss the possibilities of the photon colliders to probe these expectations. We shall in particular consider production of vector mesons in $\gamma\gamma$ and $\gamma^*\gamma$ collisions and forward jet measurement in $\gamma^*\gamma$ collisions. as a probe of the QCD pomeron. In Section 5 we discuss the spin dependent structure function $g_1^\gamma(x, Q^2)$ of the photon . Finally in Section 6 we present a brief summary of our talk.

2 Deep inelastic $e\gamma$ scattering

The deep inelastic $e\gamma$ scattering, i.e. the process:

$$e(p_e) + \gamma(p_\gamma) \rightarrow e(p'_e) + X$$

is characterised by the following kinematical variables:

$$s = (p_e + p_\gamma)^2, \quad q = p_e - p'_e, \quad Q^2 = -q^2, \quad W^2 = (q + p_\gamma)^2$$

$$y = \frac{p_\gamma q}{p_e p_\gamma}, \quad x = \frac{Q^2}{2p_\gamma q} \tag{1}$$

Possibility of precise measurement of the kinematical variables x, Q^2 in $e\gamma$ DIS is an enormous advantage of photon colliders. It is linked with the form of the spectrum of the backscattered laser photons which is more advantageous than the Weizsäcker - Williams spectrum of the (quasi) real photons exchanged in single tagged e^+e^- collisions. This in particular allows precise measurement of the photon structure function(s) with much better accuracy than in the single tagged e^+e^- collisions.

The deep inelastic $e\gamma$ scattering is related in the following way to the photon structure functions $F_2^\gamma(x, Q^2)$ and $F_L^\gamma(x, Q^2)$:

$$\frac{d\sigma(e\gamma \rightarrow eX)}{dE_{tag} d\cos\theta_{tag}} =$$

$$\frac{4\pi^2 E_{tag}}{Q^4 y} \left[(1 + (1 - y)^2) F_2^\gamma(x, Q^2) - y^2 F_L^\gamma(x, Q^2) \right] \quad (2)$$

where E_{tag} and θ_{tag} denote the energy and the scattering angle of the tagged electron.

In the leading logarithmic approximation (LLA) of perturbative QCD the structure function $F_2^\gamma(x, Q^2)$ is directly related to the quark distributions in the photon:

$$F_2^\gamma(x, Q^2) = 2x \sum_i e_i^2 q_i^\gamma(x, Q^2) \quad (3)$$

where e_i are the quark charges. Evolution of parton densities is governed by the Altarelli-Parisi equations which in the leading order take the following form [1, 2, 3, 4]:

$$\begin{aligned} Q^2 \frac{dq_i^\gamma(x, Q^2)}{dQ^2} &= \frac{\alpha_{em} N_c}{2\pi} e_i^2 k_q^\gamma(x) + \frac{\alpha_s(Q^2)}{2\pi} (P_{qq} \otimes q_i^\gamma + P_{qg} \otimes g^\gamma) \\ Q^2 \frac{dg^\gamma(x, Q^2)}{dQ^2} &= \frac{\alpha_s(Q^2)}{2\pi} \left(P_{gq} \otimes \sum_i q_i^\gamma + P_{gg} \otimes g^\gamma \right) \end{aligned} \quad (4)$$

where

$$k_q^\gamma(x) = x^2 + (1 - x)^2 \quad (5)$$

and

$$P_{ij} \otimes f = \int_x^1 \frac{dz}{z} P_{ij}(z) f\left(\frac{x}{z}, Q^2\right) \quad (6)$$

The evolution equations (4) involve, besides the quark distributions also the gluon distribution $g^\gamma(x, Q^2)$ in the photon.

The novel feature of the evolution equations for the parton distributions in the photons is the presence of the inhomogeneous term proportional to $k_q^\gamma(x)$ which corresponds to the point-like coupling of the photon to quarks (antiquarks). The solution of equations (4) for the parton distributions $f^\gamma(x, Q^2)$ in the photon ($f^\gamma = q_i^\gamma, g^\gamma$) can be written in the following form:

$$f^\gamma(x, Q^2) = f_{pl}^\gamma(x, Q^2) + f_{had}^\gamma(x, Q^2) \quad (7)$$

In this equation the distributions $f_{pl}^\gamma(x, Q^2)$ are exactly calculable (modulo dependence upon the scale Q_0^2 where $f_{pl}^\gamma(x, Q_0^2) = 0$). The hadronic component $f_{had}^\gamma(x, Q^2)$, which corresponds to the general solution of the homogeneous evolution equations depends upon the non-calculable starting distributions at the input scale Q_0^2 . Existing QCD analyses use NLO approximation in \bar{MS} or DIS_γ scheme(s) [5, 6].

In Fig. 1 we show acceptance regions and event rates which are expected to be reached at $e\gamma$ DIS for the backscattered-laser $e\gamma$ mode of a 500 GeV linear collider [7]. It can be seen from this Figure that the $e\gamma$ collider can offer opportunity to probe the very low values of x ($x \sim 10^{-4}$ for reasonably large values of $Q^2 \sim 10 GeV^2$). At NLO low x behaviour of parton distributions in the photon is dominated by a hadronic component. On the other hand at large values of x the quark distributions are dominated by the point-like term.

At low x one has also to include the low x resummation effects in the splitting and coefficient functions which are generated by the small x (i.e. BFKL) dynamics (see Sec. 5) [8]. These small x effects can significantly enhance the magnitude of the parton distributions in the photon and the photon structure function(s) at low values of x . The hadronic component remains to be the dominant contribution in this region yet the magnitude of the point like contribution is also enhanced.

At very large values of Q^2 the deep inelastic $e\gamma$ scattering can also acquire significant contribution from the Z_0 exchange. It modifies formula (2) which corresponds to the (virtual) photon exchange. Moreover at very large values of Q^2 one can have access to the charge current effects in the deep inelastic process $e + \gamma \rightarrow \nu + X$ which is mediated by the W exchange. The study of this process can in particular give information about the flavour decomposition of the quark distributions in the photon [9].

3 Gluon distribution in the photon

The gluon distribution in the photon is a poorly known quantity. In principle it can be determined from the analysis of the scaling violation of $F_2^\gamma(x, Q^2)$ generated by the evolution equations (4), but this constraint turns out to be rather weak. In order to obtain the gluon distribution it is therefore much better to study the measurements which are predominantly sensitive to the gluon content of the photon. Thus at low

x the measurement of the longitudinal structure function $F_L^\gamma(x, Q^2)$ might provide a useful constraint on the gluon distributions in the photon. The complementary and presumably much more feasible are the dedicated measurements of the hadronic final states in $\gamma\gamma$ collisions. The following two processes are of particular interest:

1. Dijet production, which contains the process

$$\gamma g \rightarrow q \bar{q}$$

2. Charm production, which is sensitive to the mechanism

$$\gamma g \rightarrow c \bar{c}$$

Since both these processes are, at least in certain kinematical regions dominated by the photon - gluon fusion mechanism as indicated above, they are sensitive to the gluon distribution in the photon. The detailed discussion of these processes is presented in this Workshop in the talks by Thorsten Wengler and Albert De Roeck [10, 11].

4 QCD at high energies

Important class of hard processes are the so called semi-hard processes in which the (large) scale Q^2 characterising the "hardness" is much smaller than the very large energy squared W^2 , i.e. $W^2/Q^2 \gg 1$. These processes are sensitive to the resummation of the powers of the new class of large logarithm $\ln(W^2/Q^2)$ in perturbative QCD calculations, i.e. they do probe the high energy limit of perturbative QCD.

The high energy limit of perturbative QCD is at present fairly well understood. The dominant contribution is given by the QCD pomeron singularity which is generated by the ladder diagrams with the (reggeised) gluon exchange along the ladder [12]. Two gluon exchange gives the energy independent cross-sections while exchange of the gluon ladder with interacting gluons generates increase of cross-sections with energy.

The sum of ladder diagrams generates the Balitzkij, Fadin, Kuraev, Lipatov (BFKL) equation:

$$f(x, \hat{k}^2) = f^0(x, \hat{k}^2) + \frac{3\alpha_s}{2\pi} K \otimes f \quad (8)$$

where $f(x, \hat{k}^2)$ denotes the unintegrated gluon distribution with x and k^2 denoting the longitudinal momentum fraction of the parent photon carried by the gluon and k^2 is the transverse momentum squared of the gluon. $f^0(x, \hat{k}^2)$ is the suitably defined inhomogeneous term.

In leading order (i.e. in the leading $\ln(1/x)$ approximation) we have:

$$K \otimes f = \int_x^1 \frac{dz}{z} \int \frac{d^2\hat{q}}{\pi\hat{q}^2} [f(z, (\hat{k} + \hat{q})^2) - \Theta(\hat{k}^2 - \hat{q}^2) f(z, \hat{k})] \quad (9)$$

The following properties of the BFKL dynamics embodied in the BFKL equation should be emphasised.

1. Diffusion of transverse momentum along the chain which should reflect itself in the hadronic final state
2. Characteristic rise with decreasing x . In LO $f \sim x^{-\lambda}$, $\lambda = 4\ln(2)3\alpha_s/\pi$
3. Large subleading effects [13]. Their major part is however understood and is under control [14].

Besides the pomeron QCD does also predict existence of the so called QCD odderon [15]. The QCD odderon corresponds to the (interacting) three gluons exchange with the three gluons coupled to the odd C, i.e. to non-vacuum quantum numbers. The intercept of the odderon is close to 1. The cross-sections generated by the odderon exchange should then be approximately independent of the incident energy.

The high energy photon colliders offer interesting opportunities to probe the QCD pomeron. It may also appear possible that the photon colliders, thanks to their very high luminosity will allow to measure rare processes generated by the odderon exchange.

The following processes are very useful tools for probing the QCD pomeron in high energy $e\gamma$ and $\gamma\gamma$ collisions [16, 17, 18]:

1. Deep inelastic $e\gamma$ scattering accompanied by a jet moving close to the direction of the photon ($x_j \gg x$, where x_j is the momentum fraction of the parent photon carried by a jet) and with $k_{Tj}^2 \sim Q^2$ [16].

2. Diffractive production of Vector Mesons in $e\gamma$ DIS, i.e.

$$\gamma^* \gamma \rightarrow V V$$

$$\gamma^* \gamma \rightarrow V X$$

3. Diffractive production of heavy vector mesons in $\gamma\gamma$ collisions

$$\gamma\gamma \rightarrow V V$$

$$\gamma\gamma \rightarrow V X$$

In Fig. 2 we show theoretical expectations for the cross-section of the diffractive J/ψ production in $\gamma\gamma$ collisions, i.e. of the process $\gamma\gamma \rightarrow J/\psi J/\psi$ [18]. Expected magnitude of this cross-section suggests that the measurement of the reaction $\gamma\gamma \rightarrow J/\psi J/\psi$ at the photon colliders should certainly be feasible.

The following processes might probe the QCD odderon [19, 20]:

1. Quasidiffractive production of pseudoscalar mesons in $e\gamma$ DIS.

$$\gamma^* \gamma \rightarrow P P$$

$$\gamma^* \gamma \rightarrow P X$$

2. Quasidiffractive production of (heavy) pseudoscalar mesons in $\gamma\gamma$ collisions

$$\gamma\gamma \rightarrow P P$$

$$\gamma\gamma \rightarrow P X$$

5 Spin dependent structure function $g_1^\gamma(x, Q^2)$

Thanks to the possibility of having polarised beams the photon colliders offer an opportunity to measure the spin dependent structure function $g_1^\gamma(x, Q^2)$ of the photon [21, 22]. This is completely unknown quantity and its measurement in polarised $e\gamma$ DIS would be extremely useful for testing QCD predictions in the broad region of x and Q^2 .

The spin dependent parton distributions in the photon $\Delta f^\gamma(x, Q^2)$ satisfy in LO Altarelli - Parisi equations similar to equations (4) with the term $k_q^\gamma(x)$ and the splitting functions $P_{ij}(z)$ being replaced by their spin dependent counterparts $\Delta k_q^\gamma(x)$ and $\Delta P_{ij}(z)$. The NLO formalism is also available. In Fig. 3 we show theoretical expectations for $\Delta u^\gamma(x, Q^2)$, $\Delta g^\gamma(x, Q^2)$ and for $g_1^\gamma(x, Q^2)$ [22]. We show results for the two model assumptions concerning the input hadronic component $\Delta f_{had}^\gamma(x, Q_0^2)$ at the reference scale Q_0^2 :

$$\Delta f_{had}^\gamma(x, Q_0^2) = f_{had}^\gamma(x, Q_0^2) \quad , \quad (10)$$

where $f_{had}^\gamma(x, Q_0^2)$ denotes hadronic component of spin independent parton distributions, and for

$$\Delta f_{had}^\gamma(x, Q_0^2) = 0 \quad (11)$$

It should be observed that the high energy photon colliders would make it possible to probe the spin dependent structure function of the photon $g_1^\gamma(x, Q^2)$ for the very small values of x where it is sensitive to the novel effects of the double $\ln^2(1/x)$ resummation [23]. Study of some dedicated measurements, like dijet or charm production in polarised $\gamma\gamma$ scattering might also give access to the spin dependent gluon distribution $\Delta g^\gamma(x, Q^2)$ in the photon.

6 Summary and conclusions

In this talk we have confined ourselves to a brief survey of the possible measurements at photon colliders which could probe photon structure and high energy limit of perturbative QCD. We have in particular emphasised the following points:

1. Photon colliders permit precise determination of kinematical variables in $\gamma\gamma$ or $e\gamma$ scattering that will allow precise measurement of quantities relevant for understanding the structure of the photon ($F_2^\gamma(x, Q^2)$, $g^\gamma(x, Q^2)$).

2. Photon colliders will give access to the (very) small x region in $e\gamma$ DIS.
3. Photon colliders will be a unique probe of the high energy limit of QCD testing effects of the QCD pomeron and possibly also the odderon exchanges. The diffractive production of J/Ψ mesons in $\gamma\gamma$ collisions is one of the very promising processes for probing the QCD pomeron at photon colliders.
4. Photon colliders offer a unique possibility to measure the spin dependent structure function $g_1^\gamma(x, Q^2)$ of the photon.

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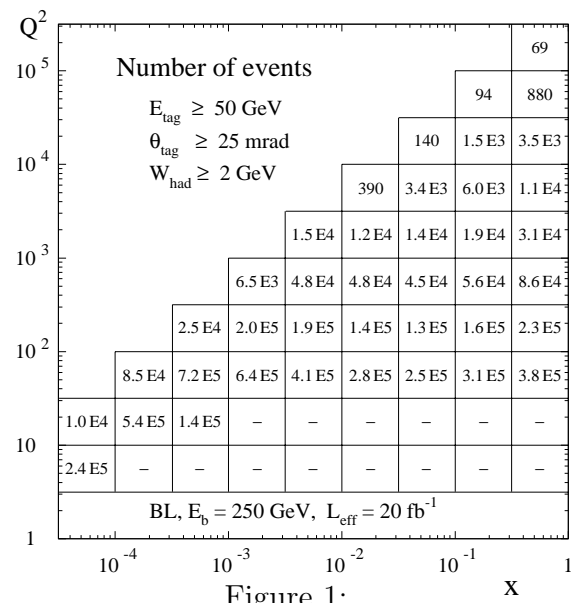


Figure 1:

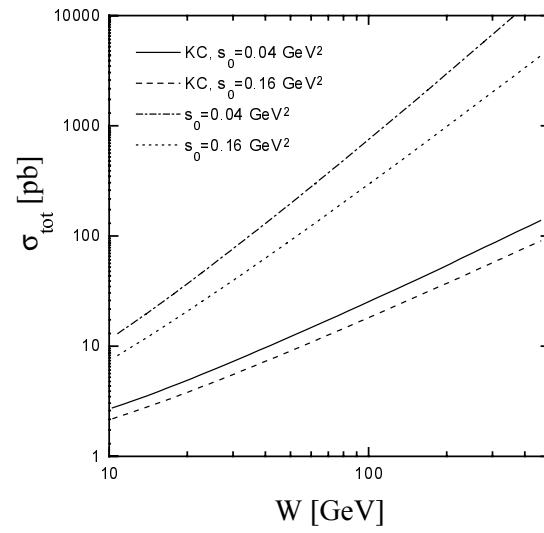


Figure 2:

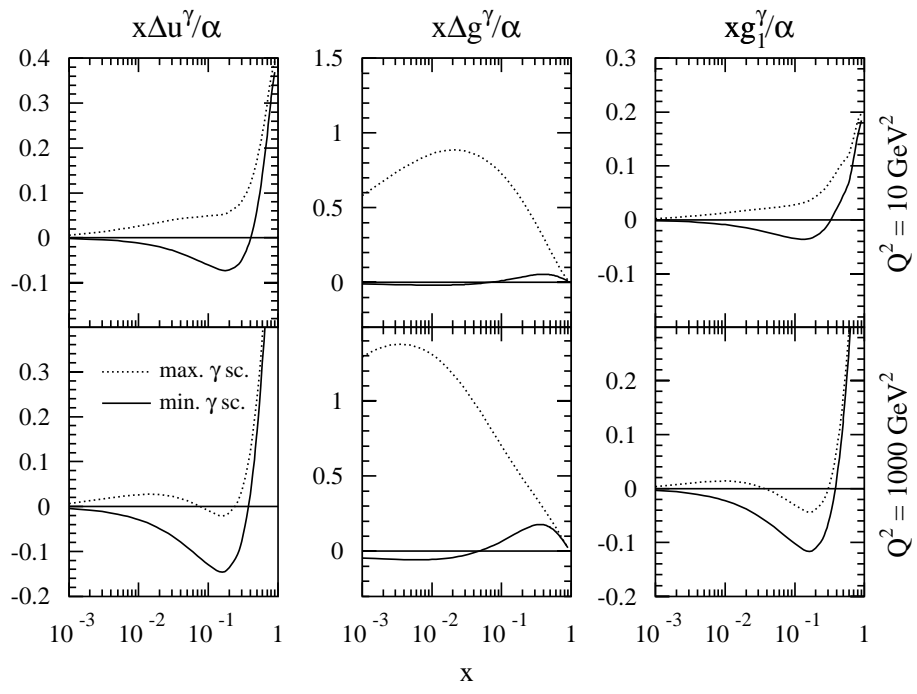


Figure 3:

Figure captions

1. Expected event numbers of electron-photon DIS for the backscattered-laser $e\gamma$ mode of a 500 GeV linear collider. It is assumed that 10% of the e^+e^- luminosity can be reached in this mode for a rather monochromatic photon beam. (From ref. [7].)
2. Energy dependence of the cross-section for the process $\gamma\gamma \rightarrow J/\psi J/\psi$. The two lower curves correspond to the calculations based on the BFKL equation with kinematical constraint generating the dominant subleading effects and the values of s_0 equal to 0.04 GeV^2 (the continuous line) and to 0.16 GeV^2 (dashed line). The two upper curves correspond to the BFKL equation in the leading logarithmic approximation with $s_0 = 0.04 \text{ GeV}^2$ (dash-dotted line) and $s_0 = 0.16 \text{ GeV}^2$ (short-dashed line). The parameter s_0 controls the contribution from the infrared i.e. confinement region. (From ref. [18].)
3. $x\Delta u^\gamma/\alpha$ and $x\Delta g^\gamma/\alpha$ evolved to $Q^2 = 10$ and 1000 GeV^2 in LO using the two extreme inputs (10) and (11). Also shown is the structure function g_1^γ in LO. (From ref. [22].)

